National Aeronautics and
Space Administration

EXPLORE SPACE TECH

Entry, Descent and Landing & Precision Landing

Michelle Munk – System Capability Leader for Entry, Descent and Landing

STMD Strategic Framework

LEAD	THRUSTS	OUTCOMES	CAPABILITIES
Ensuring American global leadership in Space Technology • Lunar Exploration building to Mars and new discoveries at extreme locations • Robust national space technology engine to meet national needs • U.S. economic growth for space industry • Expanded commercial enterprise in space	**Go** *Rapid, Safe, & Efficient Space Transportation*	• Enable Human Earth-to-Mars Round Trip mission durations less than 750 days. • Enable rapid, low cost delivery of robotic payloads to Moon, Mars and beyond. • Enable reusable, safe launch and in-space propulsion systems that reduce launch and operational costs/complexity and leverage potential destination based ISRU for propellants.	• Cryogenic Fluid Management & Propulsion • Advanced Propulsion
	Land *Expanded Access to Diverse Surface Destinations*	• Enable Lunar and Mars Global Access with ~20t payloads to support human missions. • Land Payloads within 50 meters accuracy while also avoiding local landing hazards.	• Human & Robotic Entry, Descent and Landing • Precision Landing
	Live *Sustainable Living and Working Farther from Earth*	• Conduct Human/Robotic Lunar Surface Missions in excess of 28 days without resupply. • Conduct Human Mars Missions in excess of 800 days including transit without resupply. • Provide greater than 75% of propellant and water/air consumables from local resources for Lunar and Mars missions. • Enable Surface habitats that utilize local construction resources. • Enable Intelligent robotic systems augmenting operations during crewed and un-crewed mission segments.	• Sustained human life support systems • Advanced Materials, Structures and Manufacturing • Sustainable Power • In-situ Propellant and Consumable Production • Autonomous Systems and Robotics
	Explore *Transformative Missions and Discoveries*	• Enable new discoveries at the Moon, Mars and other extreme locations. • Enable new architectures that are more rapid, affordable, or capable than previously achievable. • Enable new approaches for in-space servicing, assembly and manufacturing. • Enable next generation space data processing with higher performance computing, communications and navigation in harsh deep space environments.	• On-orbit Servicing, Assembly and Manufacturing • Small Spacecraft Technologies • Advanced Avionics • Advanced Communications & Navigation

Note: Multiple Capabilities are cross cutting and support multiple Thrusts. Primary emphasis is shown

Entry, Descent and Landing (EDL) and Precision Landing – Artemis Focus

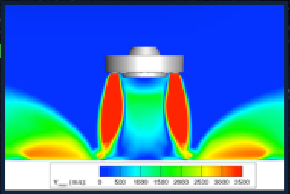
Lunar Capabilities (feeding forward to Mars)

Precision Landing and Hazard Avoidance

Safely and precisely land near science sites or pre-deployed assets

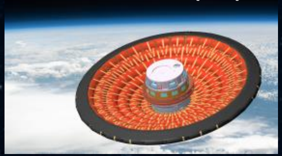
Plume Surface Interactio

Reduce lander risk by understanding how engine plumes and surfaces behave.



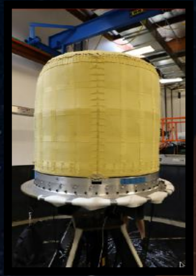
Mars Capabilities

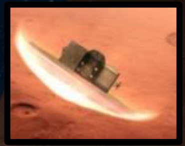
LOFTID 6m Test ('22)



Land 20 t on Mars

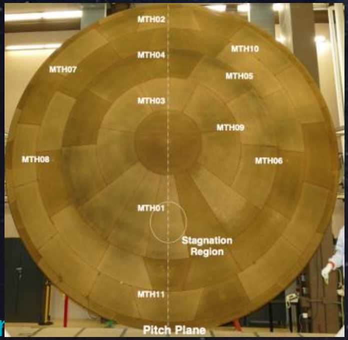
Large structures, including deployables, that can deliver high-mass payloads

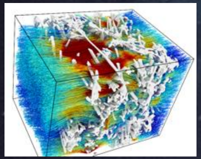




Retropropulsion Testing

Wind tunnel testing of Mars-relevant configurations; CFD modeling comparisons





Data Return and Model Improvemen

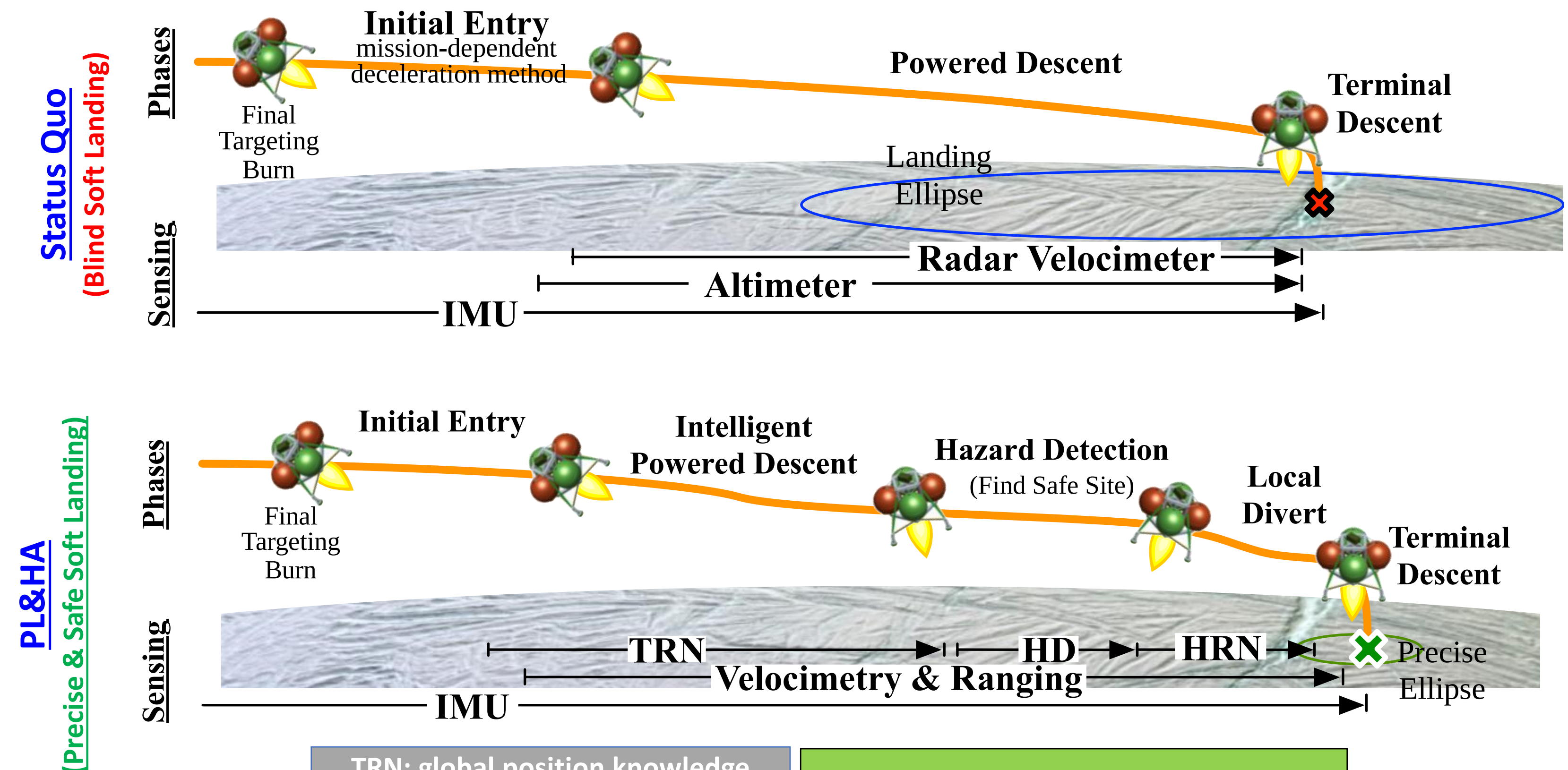
Measure EDL system performance via flight instrumentation and update unique, critical simulations for Moon, Mars, and other Solar System bodies. Includes ground-test diagnostics and uncertainty quantification; moving tools towards high-end computing capabilities and machine learning approaches.

EDL & Precision Landing Challenges (2020-40)

- Land precisely on the Moon, first with small, commercially-provided landers, then at human-scale by 2024
  - **EDL Challenges:**
    - ➢ Lightweight, cost-effective sensors for precise landing (feeds to Mars); integrating them on commercial landers with high-performing computers
    - ➢ Plume/surface/vehicle interactions near touchdown (feeds forward to Mars)
    - ➢ Integrated simulations for assessing landers and GN&C approaches (feeds forward to Mars)
- Return a sample from Mars by late 2020’s or early 2030’s
  - **EDL Challenges:**
    - ➢ Landing ~1300 kg precisely, next to samples that Mars 2020 caches
    - ➢ Autonomously launching a rocket from Mars to a target orbit
    - ➢ Returning the samples to Earth in a capsule with very low (~1×10^{-6}) probability of failure
- Explore Venus, Ice Giants, Ocean Worlds, and Outer Planets
  - **EDL Challenges:** rugged terrain, unknown atmospheres, high entry speeds. Aerocapture?
- Lower the cost of exploration
  - **EDL Challenges:** launch vehicle stage return, EDL-enabled small spacecraft, aerocapture
- Land humans on Mars
  - **EDL Challenges:** high mass, precise landing, risk posture for humans

Precision Landing & Hazard Avoidance (PL&HA)

Mission landing needs & risk posture define which PL&HA capabilities to use



TRN: global position knowledge
Minimizes landing ellipse & avoids large hazards seen in reconnaissance maps

HD & HRN: local terrain knowledge
avoid small hazards & minimize local landing error

Velocimetry & Ranging: precise soft landing
Significantly improves navigation precision

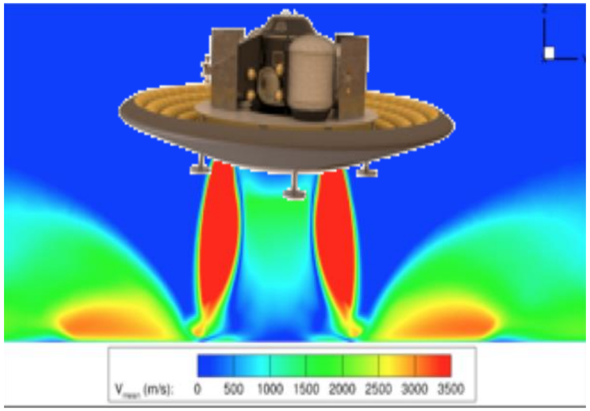
Advanced GN&C Algorithms
provide precise state knowledge and intelligent maneuvering commands

TRN	Terrain Relative Navigation
HD	Hazard Detection
HRN	Hazard Relative Navigation

Plume Surface Interaction (PSI) Focus Areas

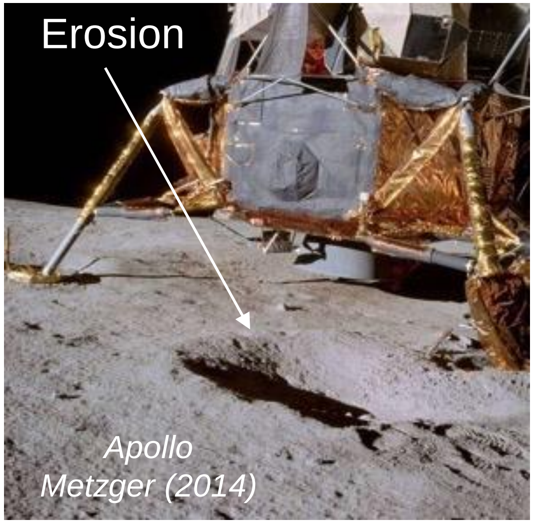
Plume Physics

- Plume effects on the lander can lead to aerodynamic destabilization and high convective heating during powered descent and landing
- Descent engine configuration is key



Site Alteration Physics

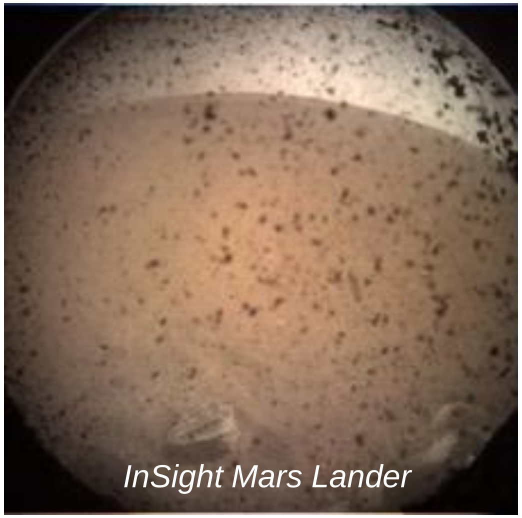
- Cratering can lead to destabilization of the lander upon touchdown and violate lander tilt requirements
- Apollo and InSight landers caused extensive erosion



Apollo
Metzger (2014)

Ejecta Dynamics

- Ejecta dynamics lead to loss of instrumentation or function, damage to the lander surrounding structure, lack of landing visibility and can spoof radar and NDL systems
- InSight initial loss of camera function and MSL sensor damaged



InSight Mars Lander

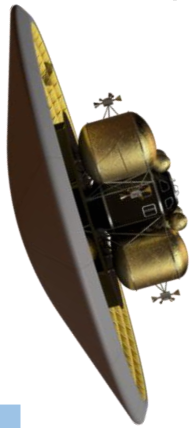
Landing 20 tonnes on Mars

Human-scale Mars landers require new approaches to all phases of Entry, Descent, and Landing

- Cannot use heritage, low-L/D rigid capsules → deployable hypersonic decelerators
- Cannot use parachutes → retropropulsion, from supersonic conditions to touchdown
- No viable alternative to an extended, retropropulsive phase of flight

	Viking	Pathfinder	MERs	Phoenix	MSL	InSight	M2020	Human-Scale Lander (Projected)
Entry Capsule (to scale)								
Diameter (m)	3.505	2.65	2.65	2.65	4.52	2.65	4.5	16 - 19
Entry Mass (t)	0.930	0.584	0.832	0.573	3.153	0.608	3.440	40 - 65
Parachute Diameter (m)	16.0	12.5	14.0	11.8	19.7	11.8	21.5	N/A
Parachute Deploy (Mach)	1.1	1.57	1.77	1.65	2.2	1.66	1.75	N/A
Landed Mass (t)	0.603	0.360	0.539	0.364	0.899	0.375	1.050	26 - 36
Landing Altitude (km)	-3.5	-2.5	-1.4	-4.1	-4.4	-2.6	-2.5	+/- 2.0
Terminal Descent and Landing Technology	Retro-propulsion	Airbags	Airbags	Retro-propulsion	Skycrane	Retro-propulsion	Skycrane	Supersonic Retropropulsion

Low-L/D



Steady progression of "in family" EDL

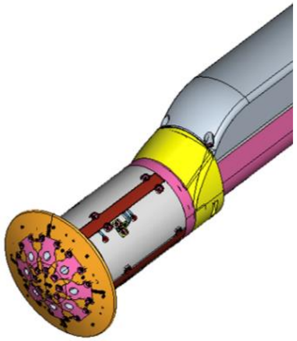
Payloads up to ~ 1 t, footprints in km

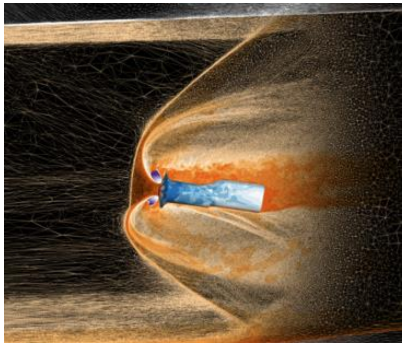
New EDL Paradigm

Payloads 20+ t, footprints < 100 m

Retropropulsion Testing and Modeling

- Human-scale and high-mass Mars landers require retropropulsion for descent and landing with potentially significant plume-induced environments
- Need to understand aerosciences implications through testing, modeling



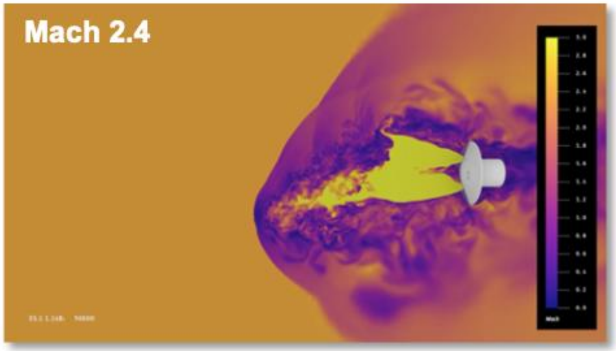


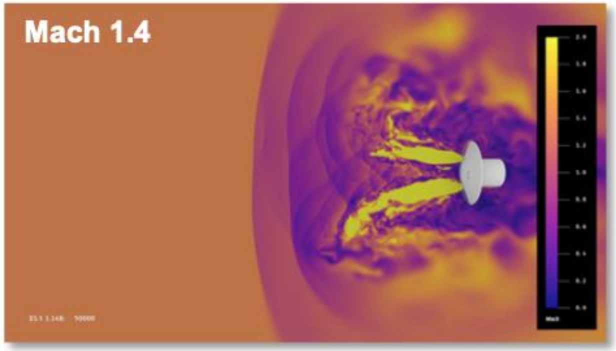
Access to DoE Summit supercomputer enabled analysis and throughput necessary:

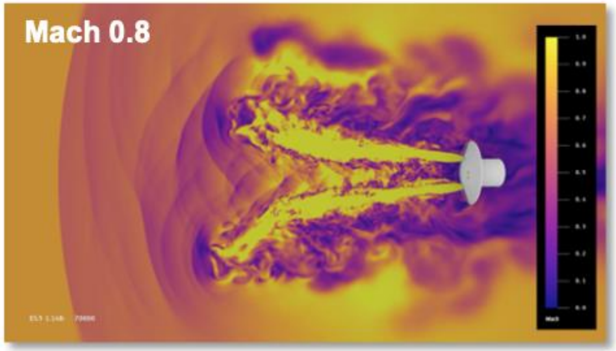
- ➢ NASA High-End Computing: 1 run in ~9 months on 5,000 CPU cores
- ➢ DoE Summit: 6 runs in ~ 4.5 days on 3,312 GPUs

Testing in supersonic wind tunnel will inform aero database for end-to-end simulation:

- ➢ Vary nozzle configuration, cant angle
- ➢ Vary Mach, thrust coefficient





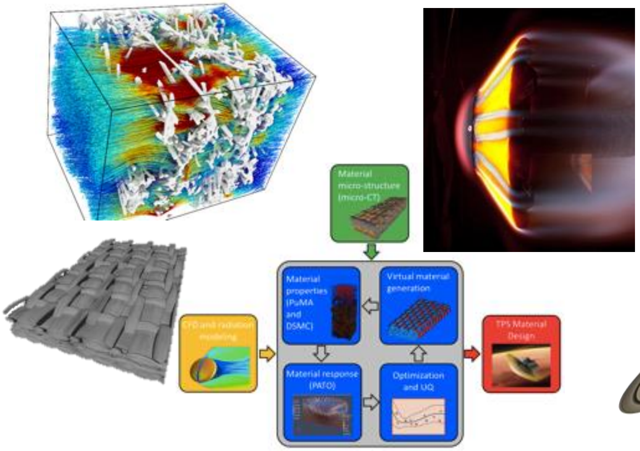


Demonstrated efficient, scalable, production-level CFD capability with GPU computing, reducing the learning cycle from *years to days*

Entry Systems Modeling (ESM) Capabilities

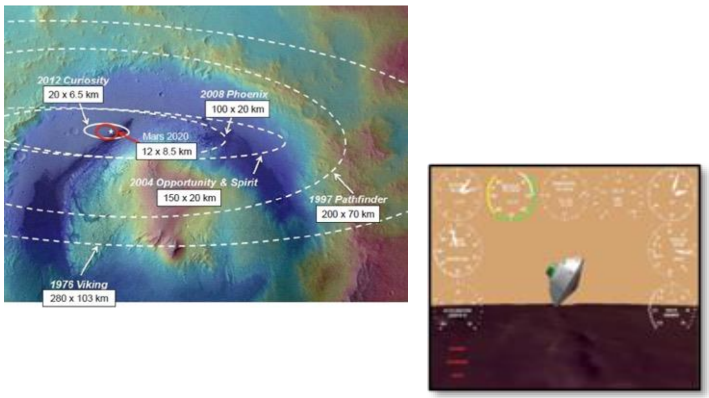
Predictive Materials Modeling

Advanced models for PICA, Avcoat and woven TPS; Micro- to engineering-scale analysis tools; Detailed material characterization and model validation



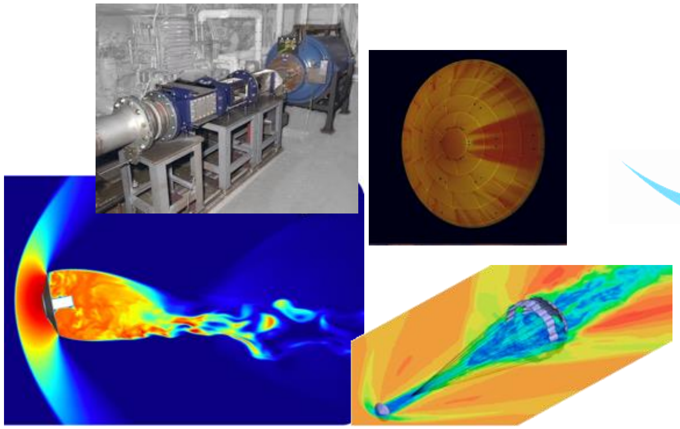
Guidance, Navigation, and Control

Entry guidance methods to enable precision landing of large robotic and human Mars missions



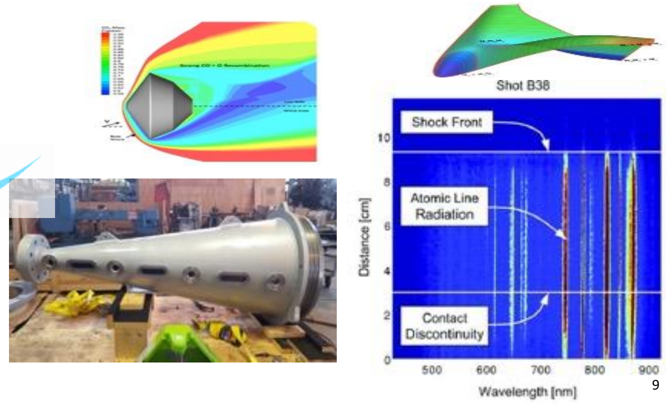
Aerosciences

Parachute dynamics; Free-flight CFD; Magnetic suspension wind tunnels; Experimental validation; Roughness, Advanced computational methods



Shock Layer Kinetics and Radiation

Radiation databases and models for Earth entry and other destinations of interest; High-fidelity coupled analysis tools



EDL & Precision Landing STP Gaps Summary

Lunar-Focused

- Land large payloads on the Moon
- Land within 50 m of desired site (develop sensors, algorithms)
- Establish consistent lunar maps
- Be able to predict Plume Surface Interaction (PSI)
- Obtain PSI flight data

Mars-Focused

- Land 20+ t on Mars
- Land within 50 m of desired site
- Establish consistent Mars maps
- Be able to predict PSI
- Conduct flight tests of hypersonic entry system
- Conduct flight tests of retropropulsion system
- Scale up large rigid, inflatable structures
- Develop landing attenuation methods

Science Mission-Focused

- Design high-reliability EDL systems
- Develop EDL/Aerocapture capability for small spacecraft
- Enable safe landing on Europa
- Develop technologies for large landers and probes
- Perform aerocapture at ice giants

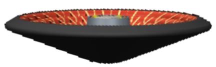
Cross-Cutting

- Improve aerodynamic and aerothermal models
- Advance flight mechanics/GN&C tools
- Establish parachute modeling
- Advance multi-disciplinary, coupled tools
- Modernize codes to GPUs; utilize high-end computing
- Instrument EDL vehicles for lower SWaP-C
- Mature TPS performance and reliability modeling
- Establish and access inexpensive flight test platforms
- Maintain and modernize unique facilities

Backup

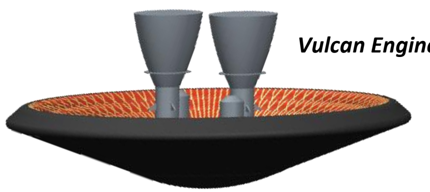
HIAD Scale-Up to Human Mars Landers

IRVE-3 (3m)



HIAD Flight Test - LOFTID (6m)

ISS Down mass (8-12m)/Guided SRP Transition Test



Vulcan Engine Recovery (12m)

Mars Ascent Vehicle HIAD (18.8m)

➢ Inflatable technology:

- Deploys a large aeroshell before atmospheric interface
- Enables landing more payload mass and/or at higher altitudes
- Reduces peak heat flux by decelerating more in less dense upper reaches of the atmosphere
- Allows payloads to use the full diameter of the launch fairing
- Stows into customized shapes for payload attachment and integrated servicing

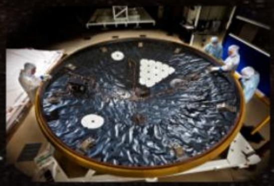
➢ Applications include:

- Robotic missions to destinations with an atmosphere (including sample return to Earth)
- ISS down mass (without Shuttle, the U.S. has no large-scale down mass capability)
- Lower cost access to space through launch vehicle asset recovery (for example, ULA’s booster module)
- High mass delivery to high altitudes at Mars (including humans to Mars)

EDL in the STMD Strategic Framework

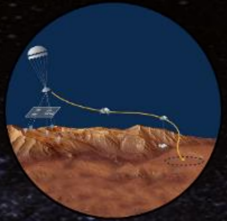
Land

Expanded Access to Diverse Surface Destinations



Mars Science Laboratory Entry Descent and Landing Instrument (MEDLI 2)

Navigation Doppler LIDAR



Terrain Relative Navigation

Mars Entry Descent and Landing

Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID)

Safe and Precise Landing – Integrated Capabilities Evolution (SPLICE)

- **Enable Lunar and Mars Global Access to land large (on the order of 20 metric tons) payloads to support human missions.**
- **Land Payloads within 50 meters accuracy while also avoiding local landing hazards.**